

METHOD AND SYSTEM FOR PRODUCTION OF FIBROUS COMPOSITE PROTOTYPES  
USING ACOUSTIC MANIPULATION IN STEREOLITHOGRAPHY

TO ALL WHOM IT MAY CONCERN:

BE IT KNOWN THAT (1) ROBERT M. KOCH and (2) ROBERT KUKLINSKI, citizens of the United States of America, employees of the United States Government, residents of (1) South Kingstown, County of Washington, State of Rhode Island and (2) Portsmouth, County of Newport, State of Rhode Island, have invented certain new and useful improvements entitled as set forth above of which the following is a specification:

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3 METHOD AND SYSTEM FOR PRODUCTION OF FIBROUS COMPOSITE PROTOTYPES  
4 USING ACOUSTIC MANIPULATION IN STEREOLITHOGRAPHY  
5

6 STATEMENT OF GOVERNMENT INTEREST

7 The invention described herein may be manufactured and used  
8 by or for the Government of the United States of America for  
9 governmental purposes without the payment of any royalties  
10 thereon or therefor.  
11

12 BACKGROUND OF THE INVENTION

13 (1) Field of the Invention

14 The present invention relates to stereolithography methods  
15 and systems involving the application of lithographic techniques  
16 to three-dimensional objects, and more particularly to providing  
17 structural reinforcement of such three-dimensional objects.

18 (2) Brief Description of the Prior Art

19 Stereolithography is a "printing" process invented by  
20 Charles Hull in 1986 by which three-dimensional copies of solid  
21 models are fabricated in plastic. This process is disclosed in  
22 U.S. Patent No. 4,575,330 to Hull, the contents of which are  
23 incorporated herein by reference. The Hull patent discloses a  
24 system for generating three-dimensional objects by creating a  
25 cross sectional pattern of the object to be formed at a selected

1 surface of a fluid medium. This fluid medium is capable of  
2 altering its physical state in response to appropriate  
3 synergistic stimulation by impinging radiation, particle  
4 bombardment or chemical reaction. Successive adjacent laminae,  
5 representing corresponding successive adjacent cross sections of  
6 the object, are automatically formed and integrated together to  
7 provide a step-wise laminar buildup of the desired object. A  
8 three-dimensional object is thereby formed and drawn from a  
9 substantially planar surface of the fluid medium during the  
10 forming process. This process was the first solid imaging  
11 process that allowed the fabrication of highly complex physical  
12 parts directly from computer generated topology data as is  
13 disclosed by Jacobs in Rapid Prototyping and Manufacturing:  
14 Fundamentals of StereoLithography (1992).

15 In fact, the advantages of stereolithography prototyping  
16 over traditional machining become even more prominent with  
17 increasing part complexity. For example, parts involving  
18 intricate internal cavities or encased subparts that are  
19 impossible to machine as one part are easily fabricated with  
20 stereolithography. Physical application of the stereolithography  
21 printing process for rapid prototyping takes place via a  
22 commercial system known as a stereolithography apparatus (SLA),  
23 manufactured by 3D Systems, Inc., Valencia, CA, which is shown in  
24 FIG. 1.

1 Referring to FIG. 1, a liquid photopolymer 10 in a vat 12 is  
2 positioned beneath a moveable HeCd laser 14. The SLA part 16 is  
3 positioned on an elevator 18. The upper surface 20 of the SLA  
4 part 16 is positioned just below the top surface 22 of the liquid  
5 photopolymer 10 so that successive layers can be added to the SLA  
6 part 16.

7 To produce a physical part, the SLA receives solid or  
8 surface model geometry data via a specifically formatted input  
9 data file known as an STL file. The STL file contains a  
10 topological representation of the part in terms of many small  
11 triangular flat-faced facets whose dimensions and orientation in  
12 space are precisely defined. The STL file "virtual" part is then  
13 mathematically "sliced" by computer software into very thin  
14 horizontal cross sections or layers. The lowest cross section  
15 data is sent to a computer-controlled optical scanning system  
16 controlling the helium cadmium (HeCd) laser 14. The laser 14  
17 draws out the shape of the cross section down onto the surface of  
18 the vat 12 of photosensitive liquid resin. Ultraviolet radiation  
19 solidifies the resin surface wherever the laser strikes, thereby  
20 precisely transforming the cross section into a thin solid layer.  
21 The process repeats itself, layer by layer, with each polymerized  
22 layer adhering to the layer below it, until a final three-  
23 dimensional physical part is produced; this layer-wise assembly  
24 is accomplished on elevator platform 18 within the vat 12 which  
25 is lowered incrementally with the creation of each new layer.

1 Finally, the full part is removed from the liquid vat and exposed  
2 to high intensity ultraviolet light to fully cure it and complete  
3 the polymerization process.

4 The SLA process was originally intended to produce  
5 prototypes for conceptual and 3D visualization purposes only.  
6 However, users of stereolithography quickly began to desire to  
7 actually test the prototypes in the laboratory. Since the first  
8 generation stereolithography polymer resins were typically  
9 brittle, low-strength, and prone to warping, second generation  
10 epoxy-based photopolymers were developed with improved mechanical  
11 properties and dimensional stability. One of these is disclosed  
12 in U.S. Patent No. 5,437,964 to Lapin et al. However, except for  
13 very carefully designed experiments as is reported, for example,  
14 by W.H. Dornfeld, (1994), "Direct Dynamic Testing of Scaled  
15 Stereolithographic Models" *International Gas Turbine and*  
16 *Aeroengine Congress and Exposition*, The Hague, Netherlands (ASME  
17 Preprint 94-GT-271), the improved polymers to date still have not  
18 achieved the mechanical strength necessary for general laboratory  
19 testing loads (e.g., high-speed in-water testing for marine  
20 applications, high-speed centrifugal loading, etc.).

21 Other prior art related to stereolithography and mixing  
22 materials into the fluid medium used in that process are  
23 summarized as follows.

24 U.S. Patent No. 5,248,456 to Evans, Jr. et al. discloses an  
25 improved stereolithographic apparatus and method. In one

1 embodiment, the improvement includes immersing at least a portion  
2 of a part in a volume of a liquid solvent in a vapor degreaser  
3 while subjecting the portion to ultrasonic agitation to  
4 substantially remove excess resin. Several examples of solvents  
5 are provided, including ethanol, and FREON<sup>TM</sup>. In a second  
6 embodiment, the improvement includes building the part on a layer  
7 of liquid resin supported by a volume of a dense, immiscible and  
8 UV transparent intermediate liquid, and integratably immersing at  
9 least a portion of the built part in the intermediate liquid, and  
10 then either subjecting the immersed portion to ultrasonic  
11 agitation to substantially remove excess resin, or subjecting the  
12 immersed portion to UV light. Several examples of intermediate  
13 liquids are provided, including prefluorinated fluids, such as  
14 FLUORINER<sup>TM</sup> FC-40 and water-based salt solution, such as solution  
15 of magnesium sulfate or sodium chloride in water.

16 U.S. Patent No. 5,296,335 to Thomas et al. discloses a  
17 method of manufacturing a three-dimensional fiber-reinforced part  
18 utilizing the single-tool method of stereolithography. The tool  
19 is fabricated by designing the tool on a computer-aided design  
20 system and curing successive layers of a fluid medium via a  
21 computer-controlled irradiation source to form the three-  
22 dimensional tool. The desired part is generated by applying  
23 layers of resin-wetted fabric to the tool, curing the fabric on  
24 the tool, removing the tool from the designed part, and cleaning,  
25 trimming and inspecting the designed part.

1 U.S. Patent No. 5,688,464 to Jacobs et al. discloses a  
2 method and apparatus for providing a vibrational enhancement to  
3 the recoating process in stereolithography. The formation of a  
4 thin layer of building material over a previous layer of  
5 structure of a partially completed three-dimensional object, in  
6 preparation for formation of an additional layer of structure is  
7 enhanced by the use of vibrational energy imparted to the  
8 building medium. In a first preferred apparatus, vibration is  
9 induced into the surface of the material by a plurality of  
10 vibrating needles that penetrate below the working surface to a  
11 sufficient depth to ensure adequate coupling but not deep enough  
12 to come into contact with the surface of the partially completed  
13 part. In a second preferred apparatus, vibration is coupled  
14 directly to the object support. The vibrational energy is then  
15 transmitted through the part to the surface of the building  
16 material. In a first preferred method, the partially completed  
17 object is overcoated with material and vibration is used to  
18 reduce the coating thickness. In a second preferred method, the  
19 partially completed object is under-coated with material and  
20 vibration is used to increase the coating thickness.

21 U.S. Patent No. 5,731,388 to Suzuki et al. discloses  
22 photocurable resins containing unsaturated urethane of a  
23 specified form and vinyl monomer which is N-  
24 (meth)acryloylmorpholine or its mixture with di-ol  
25 di(meth)acrylate at a rate within a specified range and

1 compositions containing such a resin and a filler such as solid  
2 particles and/or inorganic whiskers of specified kinds at a  
3 specified rate are capable of yielding stereolithographed objects  
4 with improved mechanical and thermal properties and form  
5 precision.

6 U.S. Patent No. 6,003,832 to Ueno et al. discloses a mold  
7 having a cavity for shaping a three-dimensional object, which  
8 comprises a photocured resin composition including a liquid  
9 photocurable resin and at least one reinforcing agent selected  
10 from the group consisting of inorganic solid particles having an  
11 average particle diameter of 3 to 70  $\mu\text{m}$  and a whisker having an  
12 average diameter of 0.3 to 1.0  $\mu\text{m}$ , a length of 10 to 70  $\mu\text{m}$  and an  
13 aspect ratio of 10 to 100 and optionally, in which the inner  
14 surface of the cavity is covered by a solid film having a  
15 thickness of 5 to 1000  $\mu\text{m}$ .

16 Unlike the common method of using the SLA prototype as "wax"  
17 masters for investment casting of metal parts as described in  
18 U.S. Patent No. 4,844,144 to Murphy et al., there have been  
19 attempts at strengthening the actual SLA prototype itself to  
20 allow its direct use in testing. The simplest, yet most limited,  
21 method is to perform post- stereolithography milling and drilling  
22 operations to allow the insertion of strengthening agents such as  
23 rods, plates, etc. Another option is to modify the SLA operation  
24 in such a way as to allow the insertion of non-polymer components  
25 (e.g., metal, ceramic) directly *during* the SLA process such as in



1 the invention describe in U.S. Patent No. 5,705,177 to Roufa et  
2 al. Another option is the deposition of various metalized  
3 coatings to the SLA prototype to both strengthen and protect it  
4 for laboratory testing purposes. Finally, U.S. Patent No.  
5 5,296,335 to Thomas et al. patented a method that utilizes  
6 stereolithography parts to create a tool and the application of  
7 resin-wetted fabric on the tool to create fiber-reinforced parts.  
8 This patent envisions the removal of the stereolithographic tool  
9 but clearly one may leave it inside if necessary for support  
10 purposes during testing.

11 While the invention of the newer more capable SLA  
12 photopolymers discussed above has been helpful in allowing  
13 carefully designed testing of SLA prototypes to occur, in general  
14 the progress has been slow and limited. Utilizing even the most  
15 advanced photopolymer in commercial use today still puts rather  
16 severe limitations on available laboratory testing of SLA  
17 prototypes.

18 The insertion of metal or ceramic structural support members  
19 via drilling and milling operations is only practical for the  
20 simplest of geometries. In a more complex SLA prototype, it may  
21 not even be possible to utilize this method due to part size,  
22 required internal voids in the part, part slenderness, drastic  
23 curves or severe changes in angular direction, or inability to  
24 support the part in a specific required direction.

1       Of the methods currently in use for structural strengthening  
2 of SLA prototypes for testing, the incorporation of external  
3 coatings discussed offers the best chance for success. However,  
4 even this method is limited to some degree to fairly simple  
5 geometries. For example, it is impossible to strengthen internal  
6 supports with this method. Clearly, this method is not  
7 complementary to the very strength of the stereolithography  
8 process - namely, the power to generate intricate, highly complex  
9 geometries with multiple internal cavities.

10       It has been well known for many years that the radiation  
11 pressure of acoustic waves may be used to control or manipulate  
12 intermittancies e.g., bubbles, particles, etc. in a fluid medium  
13 (see for example, Hanson, A.R., E.G. Domich and H.s. Adams,  
14 (1964), "Acoustic Liquid Drop Holder", *Rev. Sci. Instrum.*, Vol 35,  
15 pp. 1031-1034). In fact, this method can easily be used to cause  
16 fluid motion itself. More recently, arrays of modern acoustic  
17 transducers have been employed in more advanced ways to move and  
18 segregate particles.

19       U.S. Patent No. 4,743,361 to Schram discloses a method for  
20 separating particle types from a mixed population of particles in  
21 a liquid. This separation is obtained using an ultrasonic wave  
22 produced by interference between the outputs from spaced  
23 ultrasonic sources. One or more selected particle types may be  
24 separated by displacement axially along the standing wave or  
25 transversely through the standing wave or through combination of

1 both methods. The described separation can be achieved by  
2 control of flow of the liquid or giving the standing wave a  
3 drift, or by controlling the intensity or the frequency of the  
4 standing wave or by any combination of these factors.

5 U.S. Patent No. 4,983,189 to Peterson et al. discloses a  
6 method and apparatus for controlling the movement of materials  
7 having different physical properties when one of the materials is  
8 a fluid. The invention does not rely on flocculation,  
9 sedimentation, centrifugation, the buoyancy of the materials, or  
10 any other gravity dependent characteristic, in order to achieve  
11 its desired results. The methods of the Peterson et al invention  
12 provide that a first acoustic wave is propagated through a vessel  
13 containing the materials. A second acoustic wave, at a frequency  
14 different than the first acoustic wave, is also propagated  
15 through the vessel so that the two acoustic waves are  
16 superimposed upon each other. The superimposition of the two  
17 waves creates a beat frequency wave.

18 U.S. Patent No. 5,803,270 to Brodeur, discloses accurate  
19 ejection of liquid droplets and agitation of liquids. Oeftering,  
20 R.C., "Manipulation of Liquid by Use of Sound", NASA Tech Briefs,  
21 December, 1998, pp. 72-75, describes a very good example of a  
22 typical modern acoustic-radiation pressure phased array concept  
23 for performing such operations. The main benefit of all these  
24 acoustic manipulation inventions is their ability to exert

1 control over a fluid medium and/or objects in the fluid medium  
2 without intruding into its container as shown in FIG. 2.

3 Referring to FIG. 2, a set of left and right phased array  
4 transducers 24 and 26 are employed to nonintrusively control and  
5 manipulate the position of a dissimilar object 28 in a fluid  
6 medium 30 using acoustic radiation pressure.

7

### 8 SUMMARY OF THE INVENTION

9 It is an object of the present invention to provide a means  
10 of structural strengthening of SLA prototypes.

11 It is another object of the invention to provide structural  
12 strengthening without interfering with the ability to form  
13 complex shapes.

14 It is yet another object of this invention to strengthen an  
15 object internally.

16 Those and other objects are accomplished by the present  
17 invention, which is a method for producing a three-dimensional  
18 object by first providing a fluid medium having a top surface and  
19 which is capable of solidification when subjected to a prescribed  
20 stimulation. A solid reinforcing material is then mixed with the  
21 fluid medium. Successive cross sectional laminae are then formed,  
22 wherein each has a top surface of said object at a two-dimensional  
23 interface. These cross sectional laminae are moved downwardly as  
24 they are formed, such that there is a layer of the fluid medium  
25 between the top surface of the most recently formed lamina and the

1 top surface of the fluid medium. The object is built up in step  
2 wise fashion so that each lamina is formed from at least part of  
3 the layer of the fluid medium between the top surface of the most  
4 recently formed lamina and the top surface of the fluid. A solid  
5 reinforcing material is then mixed with the fluid medium so that  
6 at least a part of said solid reinforcing medium is located in the  
7 layer of the fluid medium between the top surface of the most  
8 recently formed lamina and the top surface of the fluid medium.  
9 An acoustic force field is then established in the fluid medium.  
10 The acoustic force field exists in at least part of the layer of  
11 the fluid medium between the top surface of the most recently  
12 formed lamina and the top surface of the fluid medium so that the  
13 solid reinforcing material is moved.

#### 14 15 BRIEF DESCRIPTION OF THE DRAWINGS

16 Other objects, features and advantages of the present  
17 invention will become apparent upon reference to the following  
18 description of the preferred embodiments and to the drawing,  
19 wherein corresponding reference characters indicate corresponding  
20 parts in the drawing and wherein:

21 FIG. 1 is a schematic cross sectional view of a prior art  
22 stereolithography apparatus (SLA);

23 FIG. 2 is a schematic drawing of a prior art concept for  
24 manipulating particles in a fluid; and

1        FIG. 3 is a cut away front elevational view of a system  
2        representing a preferred embodiment of the present invention.

3  
4                    DESCRIPTION OF THE PREFERRED EMBODIMENT

5        FIG. 3 shows an elevational view of the present invention. A  
6        stereolithography apparatus (SLA) machine 30 similar to the SLA  
7        machine shown in FIG. 1, which has been outfitted with four  
8        distributed planar acoustic arrays as, for example, arrays 32a and  
9        32b, which consist, for example, of many individually controlled  
10       piezoceramic acoustic transducer elements 34 on the interior of  
11       each of the vat's four vertical walls 36. Acoustic arrays 32a and  
12       32b are on the opposed side vertical walls 36 of the vat while two  
13       other arrays 32c and 32d are on the opposed end vertical walls 36.  
14       The four arrays 32a 32b, 32c and 32d are designed and mounted  
15       within the liquid photopolymer bath 38 in such a way as to not  
16       disrupt the workings of the perforated elevator platform 40.  
17       Additionally, the acoustic arrays 32a, 32b, 32c and 32d are  
18       positioned and oriented so that superimposed acoustic waves 42 may  
19       be generated. These waves 42 overlap in the "thin" layer region  
20       44 of liquid polymer 38 between the liquid surface 46 and the top  
21       portion of the solidified SLA part 48 for all vertical positions  
22       of the elevator platform 40. This relationship is maintained  
23       throughout the phases of fabrication. As discussed previously, the  
24       SLA machine 30 includes a laser 52 and an elevator 40. Laser 30  
25       is joined to laser positional control equipment 53, and elevator

1 40 is joined to elevator control equipment 55. Laser positional  
2 control equipment 53 and elevator control equipment 55 are joined  
3 to an SLA machine controller 57. The current invention adds an  
4 acoustic controller 54 that is joined with SLA machine controller  
5 57 for coordinating acoustic signals with the position of laser  
6 52. Acoustic controller 54 is also attached to each acoustic  
7 array as, for example, 32a and 32b for providing acoustic signals  
8 to each transducer 34.

9 The acoustic arrays as, for example, arrays 32a and 32b are  
10 used to focus an acoustic beam 42 and thereby apply acoustic  
11 radiation pressures (and thus forces) to short whisker-like fibers  
12 50 suspended within the SLA photopolymer bath 38. The  
13 superimposed acoustic waves allow manipulation and control of the  
14 positioning of the fibers 50 within the bath. Specifically, it is  
15 envisioned that these fibers 50 are directed and their position  
16 maintained in the thin layer region 44 of liquid photopolymer 38  
17 above the solidified part 48 during the laser 52 sweep portion of  
18 each SLA layer cycle. Thus, the fibers 50 will automatically be  
19 entombed in the precise desired positions within the final  
20 solidified SLA part 48. The precise focusing and positioning of  
21 the fibers 50 is accomplished via appropriately altering the  
22 amplitude, phase and frequency of the individual transducer  
23 elements 34 in the acoustic arrays, as for example, array 32a and  
24 32b using conventional acoustic beamforming practices and acoustic  
25 controller 54. In coordination with SLA machine controller 57,

1 acoustic controller 54 can manipulate fibers and particles in many  
2 different ways to give desired characteristics. A single layer  
3 can be provided with a uniform particle size or fiber orientation.  
4 Differing fiber orientations allow cross-linked strengthening of  
5 the object. The point of solidification under the laser can also  
6 be provided with a selected particle size or orientation.

7 The phased acoustic array beamforming used herein allows  
8 concentration of the fibers 50 in regular bands on a horizontal  
9 plane in the thin liquid region 44. The spacing between these  
10 rows of high concentration of fibers is dependent on the  
11 instantaneous acoustic wavelength in the photopolymer bath and can  
12 easily be controlled by altering the acoustic transducer operating  
13 frequency. The wavelength  $\lambda$  in an acoustic fluid is governed by  
14 the familiar relation  $\lambda=c/f$ , where  $c$  is the speed of sound in the  
15 fluid and  $f$  is the acoustic wave frequency. Stirring or adding of  
16 fibers is envisioned throughout the SLA prototyping process in  
17 order to keep their distribution constant.

18 It is also envisioned that the acoustic properties i.e.,  
19 mass, density and acoustic wave speed, of the fibers should be  
20 chosen so as to be amenable to acoustic pressure manipulation  
21 while being mismatched with the solidified polymer properties to  
22 avoid strongly affecting the solid part during the SLA process.  
23 Furthermore, it is advantageous to choose the optical properties  
24 e.g., wavelength and power, of the laser beam 56 and the fibers 50  
25 so that the path of the laser 56 is not greatly affected by the



1 presence of the fibers 50. Finally, any resulting surface  
2 deformation caused by the acoustic beam or superimposed acoustic  
3 waves can be controlled and limited to workable levels via  
4 appropriate modification of the amplitudes and focusing of the  
5 transducers 34.

6 In addition to obvious gravitational limitations, the size of  
7 the objects, i.e., fiber length, used for the present invention is  
8 limited to some degree by the thickness of the liquid photopolymer  
9 layer 44 being exposed by the laser on any given sweep. It is  
10 possible to increase the available object size by simply  
11 increasing the specified layer thickness during the conventional  
12 SLA slicing process. This modification is especially appropriate  
13 for fabrication of parts with more simple geometries, where a loss  
14 in vertical resolution of the final SLA part is not overly  
15 critical.

16 The method and system of the present invention provides a  
17 means for fabricating whisker fiber-reinforced prototypes  
18 directly using stereolithography. The method and system of the  
19 present invention takes advantage of the nonintrusive nature of  
20 acoustic manipulation in a fluid medium to precisely control the  
21 distribution of fibers in a SLA photopolymer bath during SLA  
22 fabrication. For the first time, it is possible to control the  
23 orientation and positioning of fibers interactively during the  
24 entire stereolithography process, ensuring the optimal

1 distribution and density of fibers throughout the final solidified  
2 part.

3 The result is a solidified fibrous composite SLA part with  
4 mechanical strength sufficient enough to allow actual laboratory  
5 testing. Additionally, in contrast to previously mentioned  
6 methods for SLA part strengthening, no post fabrication operations  
7 need be performed. Finally, the present invention requires no  
8 major modifications to conventional SLA systems and can  
9 conceivably be retrofitted to existing systems.

10 Versions of the present invention with particles replacing  
11 fibers may be constructed for the creation of particulate  
12 composite SLA prototypes.

13 The proven ability of phased acoustic array systems to  
14 segregate and control materials with different physical  
15 properties as is disclosed in U.S. Patent No. 4,743,361 to Schram  
16 and U.S. Patent No. 4,983,189 to Peterson et al. may be exploited  
17 to allow the use of both particles and fibers in the present  
18 invention for the creation of customized particulate/fibrous  
19 composite SLA prototypes. It is envisioned that the distribution  
20 of particles and fibers may be controlled during fabrication to  
21 create a solidified composite part with particles in certain  
22 desired locations and fibers in others. In fact, with sufficient  
23 signal processing and array geometries, it is even envisioned  
24 having a multiple particle sizes and multiple fiber sizes all  
25 incorporated into a single part solidification. A typical fiber

1 that may be used in the method of this invention is KEVLAR<sup>TM</sup>  
2 which are commercially available from the Dupont Corporation with  
3 headquarters at Wilmington, Delaware. Typical particles that may  
4 be used in the method of this invention are glass microspheres,  
5 which are commercially available from the 3M Corporation with  
6 headquarters at St. Paul, Minnesota.

7 While the present invention has been described in connection  
8 with the preferred embodiments of the various figures, it is to  
9 be understood that other similar embodiments may be used or  
10 modifications and additions may be made to the described  
11 embodiment for performing the same function of the present  
12 invention without deviating therefrom. Therefore, the present  
13 invention should not be limited to any single embodiment, but  
14 rather construed in breadth and scope in accordance with the  
15 recitation of the appended claims.